EVOLUTION OF DARK-MATTER HALOES IN A VARIETY OF DARK-ENERGY COSMOLOGIES

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Proceedings contribution for "Dark Matter/Dark Energy 2004"

ABSTRACT

High-resolution, numerical simulations of 17 cluster-sized dark-matter haloes in eight different cosmologies with and without dynamical dark energy confirm the picture that core halo densities are imprinted early during their formation by the mean cosmological density. Quite independent of cosmology, halo concentrations have a log-normal distribution with a scatter of $\sim$ 0.2 about the mean. We propose a simple scaling relation for halo concentrations in dark-energy cosmologies.

1. I

Having to accept that the expansion of the Universe is accelerating today and that only $\sim$ 30% of its content is contributed by matter, we need to search for what may be driving the accelerated expansion. Friedmann's equations require the dominant form of matter to have a pressure $p < -\rho c^2/3$, where ρ is its density and c is the speed of light. The cosmological constant has $p = -\rho c^2$. Generalising this, the equation of state is modified to $p = w\rho c^2$, with $w < -1/3$. In the simplest of these models, w is constant, but it is more natural to assume that w is a function of time, scale factor or redshift. One possible, admittedly hypothetical form of matter with such an equation of state is a self-interacting scalar field with an interaction potential which is sufficiently larger than its kinetic energy (e.g. Wetterich, 1988; Ratra and Peebles, 1988; Peebles and Ratra, 2002)

Replacing the cosmological constant by such a hypothetical "dark energy" has consequences for structure growth and the properties of dark-matter haloes (Bartelmann et al., 2002; Weinberg and Kamionkowski, 2003; Klypin et al., 2003). We report here on our studies of how halo concentrations change in a variety of dark-energy models (Dolag et al., 2004). This leads us to suggest a remarkably simple scaling of halo concentrations with the linear growth factor in dark-energy models. We indicate consequences for strong lensing by galaxy clusters, which offer one possibility for constraining dark-energy models. Throughout, we use present-day matter and dark-energy density parameters of $\Omega_{\mathrm{m}0} = 0.3$ and $\Omega_{\mathrm{Q}0} = 0.7$, and a Hubble constant of $h = 0.7$ in units of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2. D -E M

The continuity equation requires that the density of dark energy changes with the scale factor a as

$$\Omega_{\mathrm{Q}}(a) = \Omega_{\mathrm{Q}0} \exp\left\{-3\int_a^1 [1 + w(a')]\mathrm{d}\ln a'\right\} . \tag{1}$$

This term replaces the usual cosmological-constant term in Friedmann's equation. For w = const. = -1, the cosmological-constant behaviour is retained. For w = const., the scale-factor dependence simplifies to

$$\Omega_{\mathrm{Q}}(a) = \Omega_{\mathrm{Q}0} a^{-3(1+w)} . \tag{2}$$

If $w = -1/3$, the model behaves like an open CDM model without cosmological constant because then Ω_{Q} mimics the curvature term in Friedmann's equation.

We use one model with $w = -0.6$ = const. for reference, and two models with time-varying w. These are the Ratra-Peebles model (Ratra and Peebles, 1988) in which the scalar-field potential is a power law, and the SUGRA model (Brax and Martin, 2000) which has an additional exponential factor in the potential. Both are normalised such that $w_0 = -0.83$ at $a = 1$. While w is almost constant for the Ratra-Peebles model in the relevant redshift range, it increases from -0.83 to ~ -0.4 between redshifts 0 and 2 in the SUGRA model.

If normalised to its amplitude today, structure grows earlier in dark-energy compared to cosmological constant models. Since numerical simulations demonstrate that dark-matter haloes keep a memory in their cores of the mean cosmic density at their formation times (Navarro et al., 1997), haloes forming earlier are expected to have higher core densities. Thus, at fixed mass and redshift, haloes are expected to be more concentrated in dark-energy than in cosmological-constant models. This was expected from analytic considerations. The work reported here aims at testing this expectation with numerical simulations.

3. N S

Using the Gadget code (Springel et al., 2001), we ran a large-scale cosmological simulation of the ΛCDM model, identified massive haloes within it, identified their Lagrangian volumes at the initial redshift, added small-scale power and re-simulated them at much increased resolution (Tormen et al., 1997). The particle mass is $5 \times 10^9\,h^{-1}\,M_\odot$. We thus created a sample of 17 clusters with final masses between 3×10^{14} and $2 \times 10^{15}\,h^{-1}\,M_\odot$. The ΛCDM simulation was normalised to $\sigma_8 = 0.9$.

We then re-simulated this same cluster sample in dark-energy cosmologies. For doing so, we shifted the initial redshift of the simulation to higher values such that the earlier structure growth in the dark-energy models was compensated. For achieving the same density-fluctuation normalisation today, the initial redshift z_{ini} of the dark-energy simulations needs to satisfy

$$\frac{D_+(z_{\mathrm{ini}})}{D_+(0)} = \frac{D_{+,\Lambda\mathrm{CDM}}(z^{\mathrm{ini}}_{\Lambda\mathrm{CDM}})}{D_{+,\Lambda\mathrm{CDM}}(0)} , \tag{3}$$

where $D_+(z)$ is the linear growth factor as a function of redshift,

and $z^{\rm ini}_{\Lambda\rm CDM}$ is the initial redshift of the ΛCDM simulation. It is important to also rescale the initial velocities of the simulation particles to the higher initial redshift.

The normalisation of the models is an open issue. The earlier structure growth in dark-energy models increases the Integrated Sachs-Wolfe effect and thus the amplitude of large-scale secondary fluctuations in the CMB. A smaller fraction of the observed fluctuations can then be attributed to the primordial CMB, thus the normalisation of the power spectrum should be lowered.

However, we are interested in the properties of dark-matter haloes whose linear scale is much smaller than that of the Sachs-Wolfe tail in the CMB power spectrum. How the large-scale amplitude measured by on CMB translates to small scales depends sensitively on the large-scale slope of the density power spectrum. We argue that weak gravitational lensing directly measures the power-spectrum amplitude at the scales relevant here and should thus develop into the prime method for normalising the power spectrum at small scales. For now, we study two sets of normalisations. One has constant $\sigma_8 = 0.9$ for all cosmological models, the other has reduced σ_8 such as to take the enhanced ISW effect into account.

In total, we simulate our sample of 17 clusters in eight different cosmologies: ΛCDM, Ratra-Peebles, SUGRA, and $w = -0.6$, the latter three with two different normalisations each, and an open-CDM model with $\Omega_\Lambda = 0$ for comparison.

4. R

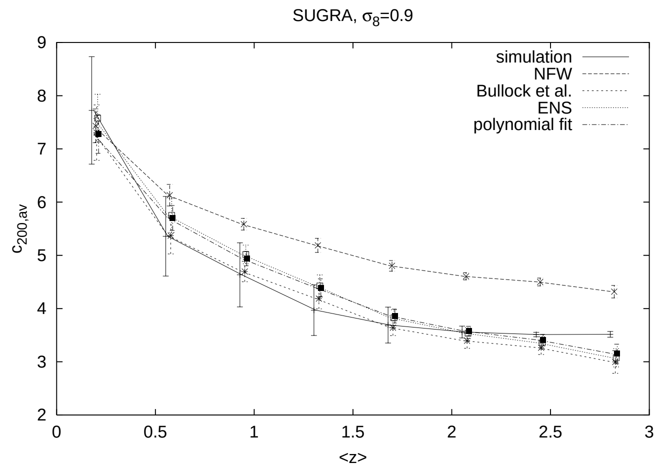
We fit the NFW density profile to all clusters and obtained concentration parameters for all of them at 50 output redshifts between $z = 3$ and today. For all these cluster snapshots, we also compute analytically expected concentrations according to the algorithms proposed by Navarro et al. (1997); Bullock et al. (2001); Eke et al. (2001). These algorithms implement in different ways essentially the same idea: The core halo density is determined by the mean cosmological density at the halo formation redshift, which is typically defined as the redshift when the most massive progenitor of the final halo reaches a certain small fraction of the final halo mass. The factor between the mean cosmological density and the halo core density, and the fraction of the final halo mass used for defining the halo formation redshift, are two free parameters in the algorithms by Navarro et al. (1997) and Bullock et al. (2001). The algorithm by Eke et al. (2001) has only one free parameter. We determine these parameters by minimising the squared deviation between the analytic halo concentrations expected for the given halo masses and redshifts, and the numerically-determined halo concentrations.

We find that excellent agreement between the numerical halo concentrations and the predictions by the algorithm of Bullock et al. (2001) can be achieved if haloes are assumed to form very early, or, in other words, if we assume that halo core properties are imprinted when only a very small fraction of the final halo mass is already in place. The results from the algorithm of Eke et al. (2001) agree very well with the numerical concentrations without any parameter adaptation, while the Navarro et al. (1997) algorithm predicts too shallow redshift evolution (cf. Fig. 1).

Our results admit a power-law fit of the form

$$\bar{c}(M,z) = \frac{c_0}{1+z}\left(\frac{M}{10^{14}\,h^{-1}\,M_\odot}\right)^{\alpha}\;, \tag{4}$$

where c_0 is a constant for each cosmology. The exponent $\alpha \approx -0.1$ for all cosmologies tested, thus the mass-dependence of the



F . 1.—Example for the agreement between analytically expected and numerically determined halo concentrations in the SUGRA model normalised to $\sigma_8 = 0.9$. The solid line with the error bars shows our numerical results in eight redshift bins between redshifts 3 and 0. “NFW” and “ENS” stand for Navarro et al. (1997) and Bullock et al. (2001), respectively.

T 1.—Parameters c_0 and α for the fit formula (4) for halo concentrations in our eight cosmological models.

model	σ_8	c_0	α
ΛCDM	0.90	9.59 ± 0.07	−0.102 ± 0.004
Ratra-Peebles	0.90	10.20 ± 0.07	−0.094 ± 0.005
Ratra-Peebles	0.82	9.30 ± 0.06	−0.108 ± 0.005
SUGRA	0.90	11.15 ± 0.09	−0.094 ± 0.006
SUGRA	0.76	9.46 ± 0.07	−0.099 ± 0.005
$w = -0.6$	0.90	11.32 ± 0.09	−0.092 ± 0.005
$w = -0.6$	0.86	10.44 ± 0.08	−0.066 ± 0.005

halo concentrations is quite shallow for massive haloes. Table 1 summarises the parameters we find.

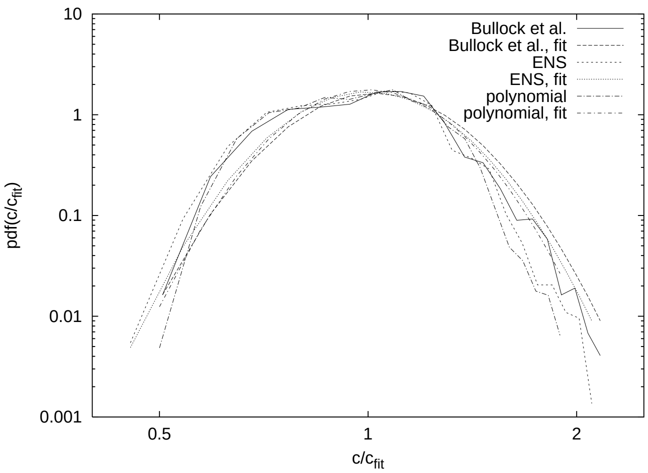
The scatter among the concentrations is large, but well-described by a log-normal about the mean given by (4). Quite independent of the cosmological model, the standard deviation of $\ln(c/\bar{c})$ is ≈ 0.22 (cf. Fig. 2), see also Jing (2000).

Interestingly, it turns out that a simple description can also be given for the cosmology-dependence of the parameter c_0. We find $c_0^{\Lambda\rm CDM} \approx 9.6$, and for the other cosmological models

$$c_0 = c_0^{\Lambda\rm CDM}\,\frac{D_+(z_{\rm coll})}{D_+^{\Lambda\rm CDM}(z_{\rm coll})}\;, \tag{5}$$

i.e. the concentrations scale in proportion to the linear growth factor, provided that the halo collapse redshift $z_{\rm coll}$ is chosen high enough; in fact, even $z_{\rm coll} \to \infty$ produces good agreement with the numerical simulations. This reinforces the impression that halo properties are imprinted at very early times, when only a very small fraction of the final halo mass is already in place.

The higher halo concentrations found in dark-energy cosmologies are expected to have pronounced consequences for strong gravitational lensing by galaxy clusters. This is indicated by an analytic study we have carried out, and demonstrated by a numerical study using the same cluster sample described here (cf. the contribution of Meneghetti et al. to these proceedings).



F . 2.—Quite independent of cosmology, the halo concentrations fall on a log-normal distribution with a scatter of ≈ 0.22.

5. C

Using numerical simulations of 17 cluster-sized haloes in eight different cosmologies, we have tested and confirmed analytic expectations for the dependence of halo concentrations on models for the dark energy. Earlier structure growth in dark-energy models yields more concentrated haloes. If it is assumed that core halo properties are imprinted at very early times, when only a very small fraction of the final halo mass is already in place, the halo-concentration algorithms proposed by Bullock et al. and Eke et al. turn out to work remarkably well. Halo concentrations have a log-normal distribution with a scatter of $\approx$ 0.22 about their mean values, quite independent of cosmology. For all cosmologies tested, the mean halo concentration at fixed mass and redshift scales in proportion to the linear growth factor at the halo formation time if the latter is defined to be very early.

A

We are grateful to Volker Springel for his code and support, and to Simon White for his constructive comments. The simulations were carried out on the IBM-SP4 machine at the "Centro Interuniversitario del Nord-Est per il Calcolo Elettronico" (CINECA, Bologna), with CPU time assigned under an INAF-CINECA grant. K. Dolag acknowledges support by a Marie Curie Fellowship of the European Community program "Human Potential under contract number MCFI-2001-01227.

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